Overview of the T2K Experiment

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~500 scientists from 59 institutes in 11 countries

295 km
Physics Goals of T2K

- Neutrino Oscillations
  - Precision measurements of known oscillation parameters
    - $|\Delta m_{23}^2|$, $\theta_{13}$, $\theta_{23}$
  - First measurement of $\delta_{\text{CP}}$
  - Determine mass hierarchy

- Neutrino-Nucleus Cross Sections
  - High statistics measurements of various inclusive final states for NC, $\nu_\mu$CC, $\bar{\nu}_\mu$CC, and $\nu_e$CC
  - Measure on various targets
    - e.g. C, O, Ar, Pb, Fe

- BSM searches
  - Sterile neutrino oscillations
  - Lorentz invariance violation (LIV)
  - $\nu$ TOF

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Off-axis beam gives higher flux in region of interest for oscillations.
Added benefit of dominant interaction type (CCQE) allows for accurate energy reconstruction in nu. osc.

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Neutrino Beam Line

Protons are accelerated at J-PARC facility in Tokai, Japan to 30 GeV before being extracted into the T2K beamline.

Protons collide with graphite target
Mesons are focused by 3 horns into a 96m long decay volume

Have just completed T2K's first $\bar{\nu}$ run
Total POT so far: $7.39 \times 10^{20}$ POT
$\bar{\nu}$ Beam so far: $6.88 \times 10^{20}$ POT
$\bar{\nu}$ Beam so far: $0.51 \times 10^{20}$ POT

Data used in analyses shown in this conference: $6.57 \times 10^{20}$ POT
On-Axis Detector (INGRID)

- Modular detector in cross
  - Iron planes sandwiched between scintillator x-y layers

- Center of detector aligned with beam center
  - Redundant measurement of off-axis angles up to 2.5°
  - Monitor neutrino beam direction and beam profile w/ high statistics

- Measure $\nu_\mu$-Fe+hydrocarbon cross section
  See talk from B. Quilain for more

- LIV searches
Off-Axis Detector (ND280)

UA1 Magnet: 0.2 T magnetic field

Tracker:
- Fine Grain Detectors (FGDs)
- Time Projection Chambers (TPCs)
- Good vertex & momentum reconstruction

P0D (π^0 Detector):
- Measure NCπ^0 background (ν_e appearance)

ECALs:
- Provide more information on particles escaping tracker & P0D

SMRD:
- Provides information on muons ranging out

Constrain flux and cross section uncertainties for oscillation analyses

- Inclusive cross section measurements
  - Can be subdivided based on particles in final state
- BSM searches
  - Short-baseline sterile neutrino searches
  - LIV

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Sampling of Near Detector Results

Runs 1-4 INGRID $\nu_\mu$ CC-inclusive flux-averaged cross section on CH

arXiv: 1407.4256 (hep-ex)

Runs 1-4 ND280 $\nu_\mu$ CC-inclusive flux-averaged cross section on CH

arXiv: 1407.4256 (hep-ex)

See talks from J. Zalipska, B. Quilain, & M. Rayner for more
$\mu^+: p = 572\pm39$ MeV/c
Super-Kamiokande

- 50 kT water Cherenkov Detector
- Multi-purpose detector
- Including T2K’s far detector
- Good $e/\mu$ separation
- Good $E_\nu$ reconstruction
- NC cross section measurements

Fiducial Volume (FV): 22.5 kT
Selections for oscillation analyses require all events are \textit{w/in} SK's FV, leave all their energy in inner detector, & have 1 ring
\begin{itemize}
  \item $\nu_\mu$ disappearance (1R$\mu$): $\mu$-like ring, $p>200$ MeV/c
  \item $\nu_e$ appearance (1Re): $e$-like ring, $E_{\text{vis}} > 100$ MeV, $E_{\nu,\text{Rec}} < 1250$ MeV, $\pi^0$ rejection cut applied
\end{itemize}
2 Flavor $\nu_\mu \rightarrow \nu_e$ Appearance

- Fit to either reconstructed neutrino energy or outgoing electron p-\(\theta\) (shown) from 1Re sample using likelihood
- Does not explicitly use T2K $\nu_\mu$ disappearance results
- Interplay of mixing angle in osc. prob.
- Fit assumes either normal or inverted mass hierarchy (i.e. which mass eigenstate is heaviest) as well as other oscillation parameters

<table>
<thead>
<tr>
<th>Hierarchy</th>
<th>Normal</th>
<th>Inverted</th>
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<tbody>
<tr>
<td>Best fit of $\sin^2 2\theta_{13}$</td>
<td>0.140</td>
<td>0.170</td>
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<tr>
<td>90% C.L. range</td>
<td>0.090-0.205</td>
<td>0.111-0.246</td>
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- See non-zero $\theta_{13}$ at $7.3\sigma$
- Tension in $\theta_{13}$ that may be a hint of CP violation in the leptonic sector
3-Flavor Joint Oscillation Results (T2K-Only)

- Fit 1Re & 1Rμ samples simultaneously
- 2 Oscillation Analyses (different methods) for Runs 1-4
  - Markov Chain Monte Carlo (shown)
  - Likelihood ratio
  - Results are consistent
  - Also analyzed with reactor constraint
  - See A. Kaboth's talk for more

- With $6.57 \times 10^{20}$ POT, T2K:
  - Has world's best measurement of $\theta_{23}$
  - Is competitive w/ MINOS for $|\Delta m_{23}^2|$
  - Tension in $\theta_{13}$ that may be a hint of CP violation in the leptonic sector

- Have more events to analyze including upcoming beam time
Summary & Future Sensitivities

• T2K has successfully completed 5 run periods to date
  – Including an antineutrino run
  – ~7.4x10^{20} POT integrated
    • 6.5x10^{20} POT for analyses shown
• Large and varied physics program
  – Neutrino oscillations
    • Including world's best $\theta_{23}$ measurement
  – Neutrino-nucleus cross sections
  – Exotic searches
• See other talks for exciting details

50% running for $\nu$ & $\bar{\nu}$; assumes $\sin^22\theta_{13} = 0.1$, $\Delta m^2_{23} = 0.0024$ eV$^2$, 7.8x10$^{21}$ POT, and current systematic errors
BACKUPS
Hadron production experiment at CERN
31 GeV/c proton beam
Thin & T2K replica target data taken for T2K
Overlaps well with T2K phase space (shown is thin target data)
Tune data to NA61 measurements
Use errors for external constraint on flux errors
Neutrino Interaction Generators

Model neutrino interactions on various nuclear targets (NEUT/GENIE)

CCQE/NCEL: Smith Moniz for nuclear targets

Resonant production & coherent $\pi$ production: Rein & Sehgal

DIS: GRV98 PDF w/ Bodek-Yang correction

Intranuclear effects: cascade model (NEUT)

- Gives (in combination w/ flux simulation) prediction of total event rate, background contamination, and kinematics
- Needs to be well understood due to various processes turning on in region of interest
- Most model parameters are reweightable, meaning we can get prior errors for oscillation analyses on the model (esp. when comparing to external data sets)
- Implemented since these analyses: spectral function for nuclear environment in CCQE interactions; Nieves model for npnh